Advantages and limitations of L-band bistatic radar remote sensing of landscape freeze/thaw state

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***Abstract* – This paper presents results from recent satellite Global Navigation Satellite System-Reflectometry (GNSS-R) experiments in the northern high latitudes. Seasonal changes in the reflected signal are attributed to changes in the freeze/thaw state of the landscape. Here, we describe the unique geometries and sampling strategies that GNSS-R provide, which come with both advantages and limitations vis-à-vis traditional remote sensing techniques for monitoring the freeze/thaw transition. We will compare observational GNSS-R data in the northern high latitudes with cotemporaneous L-band radiometer and radar data to highlight these advantages and limitations.**

Index Terms— Freeze/thaw, GNSS reflectometry, bistatic radar

1 INTRODUCTION

Monitoring the evolution of landscape freeze/thaw (F/T) state is important for understanding carbon fluxes and hydrological processes in the northern high latitudes. Landscape F/T state, which describes whether the water content in different components of the landscape (soil, vegetation) is liquid or solid, is often considered to be a hydrologic and biologic on/off switch [1]. During the winter months when the landscape is primarily frozen, carbon uptake and release by plants as well as microbial activity is limited due to the lack of liquid water. The spring thaw brings a flourish of vegetative and microbial activity, with the transition between frozen to thawed conditions often occurring in a matter of days, though the transition is highly heterogeneous depending on topographic characteristics, such as slope and aspect [2]. Recent research is also showing that the transition from thawed to frozen conditions is poorly understood in terms of carbon release, and the persistence of a subsurface thawed layer of soil may contribute significantly to the annual carbon budget in the high latitudes [3].

The timing of the seasonal F/T cycle has changed and is continuing to change due to a warming climate, with records showing a lengthening of the growing season in the high latitudes by eight days between 1988 and 2001 [4]. Future changes in the climate of the northern high latitudes may not be linear [5]. These changes are critical to monitor because it is not yet known whether future warming will result in the high latitudes becoming a source or a sink for carbon [6].

Due to a dearth of *in situ* observational data, remote sensing is the only viable method to obtain consistent and broad-scale information about F/T state [2]. The rapid and high spatially heterogeneous F/T transitions require observations with high rate (daily-three days) temporal revisit times in addition to observations at the landscape scale (hundreds of meters-few km). This presents a challenge to traditional remote sensing instruments, which usually have a tradeoff between high-rate temporal or spatial sampling. One way to obtain these measurements at the required temporal and spatial scales is using a constellation of small satellites. Launching a constellation of active radars, which is the ideal sensor for assessing F/T state, would be prohibitively expensive, but the opportunity exists to leverage existing constellations of L-band transmitters that comprise the Global Navigation Satellite System (GNSS) constellations. In this case, a constellation of receivers could be launched at a fraction of the cost. The use of GNSS reflected signals as a form of bistatic radar is called GNSS-Reflectometry, or GNSS-R.

There are currently two sources of spaceborne GNSS-R data with observations in the northern high latitudes: TechDemoSat-1 (TDS-1), which was launched by Surrey Satellite Technology Ltd in 2014, and the retuned Soil Moisture Active Passive (SMAP) radar receiver, which has been collecting GNSS reflections since August 2015. Recent work has already shown that GNSS-R data collected by the SMAP radar receiver are sensitive to F/T transitions. Here, we analyze TDS-1 data along with cotemporaneous L-band monostatic radar and radiometer datasets to elucidate under what conditions the GNSS-R, monostatic radar, and radiometer instruments are more sensitive and successful in terms of retrieving landscape F/T state.

2 OBSERVATIONS

This section describes the different data sets used for comparison in this study.

2.1 GNSS-R data

As described above, there are two sources of spaceborne GNSS-R data in the northern high latitudes: TDS-1 and the retuned SMAP radar receiver. Each instrument provides data in the form of delay-Doppler maps (DDMs), which are two-dimensional cross-correlations between the received GNSS signal and a locally-generated replica signal, which is different for each GNSS satellite. An example of a DDM is shown in Figure 1. The peak power of each DDM is related to the characteristics

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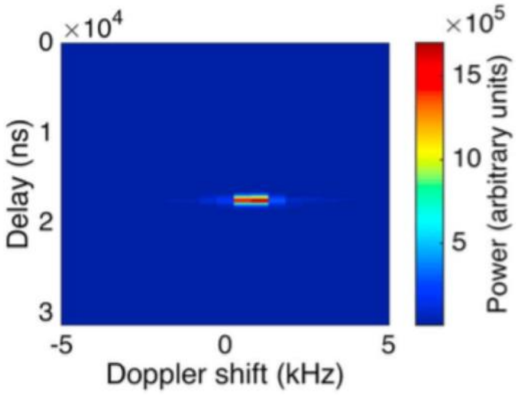

Figure 2: A delay-Doppler map recorded over a floodplain. The peak value (in red) is sensitive to changes in the freeze/thaw state of the surface.

of the land surface, specifically the dielectric constant and surface roughness. Because the dielectric constant of the land surface decreases significantly after freezing, the peak power of the DDM is sensitive to the F/T transition. The peak power of each DDM reflection must be first corrected for antenna gain and range before it can be analyzed for its response to the F/T transition. The corrected peak power, which is normalized to the noise floor of the DDM, is reported as the signal-to-noise ratio (SNR).

2.2 L-band monostatic radar data

Two sources of L-band monostatic radar data are available for the time period during which there are cotemporaneous GNSS-R observations—SMAP and PALSAR-2. PALSAR-2 acquisitions are available for the time period of both SMAP reflection observations as well as TDS-1 data. The SMAP radar, although its time period of operability was quite short, do have some overlap with the TDS-1 acquisitions.

2.3 L-band radiometer data

For this study, we examine how changes in brightness temperatures from the SMAP radiometer in the northern high latitudes correlate with changes in the GNSS-R data. SMAP also provides a F/T retrieval derived from the brightness temperature observations, which we will also compare to the GNSS-R data.

3 RESULTS

Figure 2 (a,b) shows the observed change in SNR from TDS-1 due to changes in F/T state, as indicated by the SMAP radiometer product [7]. Here we only present changes in SNR for collocated surface

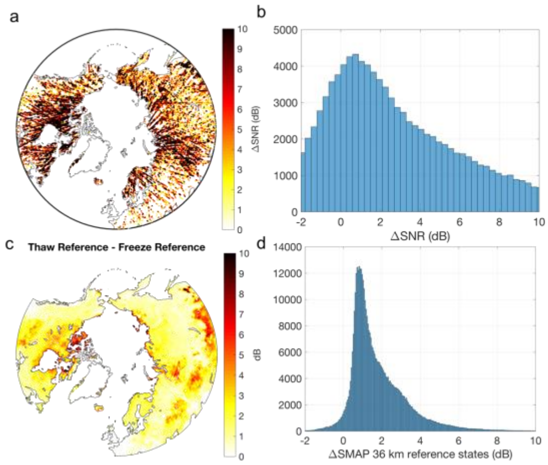

Figure 1: (a) Change in SNR from TDS-1 for areas with collocated reflections. Here, we show collocated reflections for which one reflection was recorded while the soil was thawed (as indicated by the SMAP radiometer F/T product) and one was recorded while the soil was frozen. (b) Histogram of changes in SNR for the points in (a). (c). Sensitivity of the SMAP radiometer product to changes in F/T state, as reported in [7].

reflections—reflections recorded in nearly the same location but at different times. In this case, the change in SNR is the change between thawed and frozen states, such that a positive change indicates that SNR decreased when the surface froze. SNR changes the most in areas of the northern high latitudes that are known for having large amounts of either surface water or saturated soil (Figure 2a). Figure 2b shows the distribution of SNR change that is plotted in Figure 2a—the distribution has a non-zero mean with a large amount of right-tailed skewness.

Figure 2c shows the difference in the reference states for frozen and thawed conditions that are used to create the SMAP radiometer F/T product. This figure shows that the radiometer is also more sensitive to changes in F/T states in areas where the soil is saturated, and the spatial patterns of change are similar to those exhibited by the GNSS-R data. Figure 2d shows the distribution of Figure 2c. Again, similar to the GNSS-R data, the changes in SMAP reference states also have a similar non-zero mean with a right-tailed skewness, though preliminary observations from this figure alone might suggest that SNR changes on the whole are greater than those expected from the radiometer. More analysis is need to substantiate this claim, however.

4 SUMMARY

This study presents observational evidence that spaceborne GNSS-R data are sensitive to changes in landscape F/T state. Given that the spatial resolution of reflection data over land is relatively small (few km) and could theoretically be provided globally at sub-weekly temporal resolution or less, GNSS-R could be an innovative way to provide better or at least complementary datasets to improve understanding of how the northern high latitudes continue to evolve in the future.

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